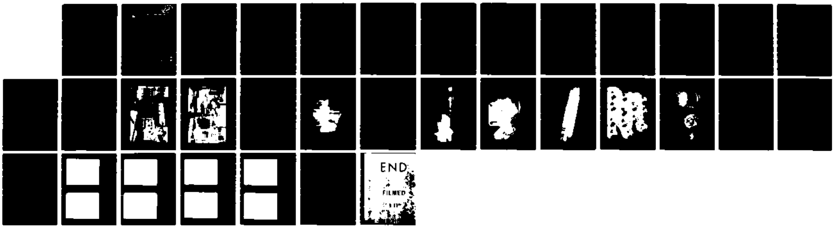
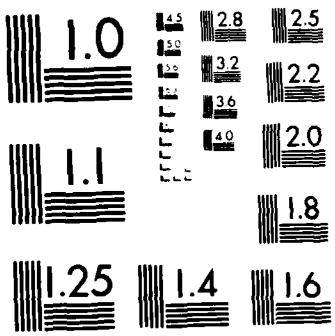
AD-A131 386 PREDICTION OF HYDRAULIC PUMP FAILURES THROUGH WEAR DEBRIS ANALYSIS(U) NAVAL AIR ENGINEERING CENTER LAKEHURST NJ GROUND SUPPORT EQUIPMENT DEPT 1/1

UNCLASSIFIED P V CIEKURS ET AL. 19 JUL 83 NAEC-92-171 F/G 5/1 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

12

NAVAL AIR ENGINEERING CENTER

REPORT NAEC-92-171

LAKEHURST, N.J.
08733

PREDICTION OF HYDRAULIC PUMP FAILURES THROUGH WEAR DEBRIS ANALYSIS

Advanced Technology Office
Support Equipment Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

19 July 1983

Final Report
AIRTASK A31-340A/051B/3F41460000

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

Prepared for

Commander, Naval Air Systems Command
AIR-313A
Washington, D.C. 20361

NAEC-92-171

PREDICTION OF HYDRAULIC PUMP FAILURES THROUGH WEAR DEBRIS ANALYSIS

Prepared by: P.V. Ciekurs
P. V. Ciekurs, PE
Advanced Technology Office (92A3)

Approved by: F. E. Evans
F. E. Evans
Support Equipment Engineering
Superintendent

7-19-83 104

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NAEC-92-171	2. GOVT ACCESSION NO. AD-A131386	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PREDICTION OF HYDRAULIC PUMP FAILURES THROUGH WEAR DEBRIS ANALYSIS		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER NAEC-92-171
7. AUTHOR(s) P. V. Ciekurs S. A. Ropar* V. T. Kelley		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Air Engineering Center Advanced Technology Office (92A3) Lakehurst, NJ 08733		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AIRTASK A31-340A/051B/3F41460000 WF 41-46
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command AIR-313A Washington, D.C. 20361		12. REPORT DATE 19 July 1983
		13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*North American Aircraft Operations/Rockwell International Columbus, OH.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wear Debris Analysis
Oil Analysis
Ferrography
Tribology

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes an investigation into the feasibility of monitoring hydraulic system wear debris characteristics in order to predict failures. The investigation utilized hydraulic pumps from an RA-5C aircraft hydraulic system and was monitored by spectrometric analysis and ferrography. Based on one relevant failure it was determined that ferrography can predict a failure of a pump prior to its occurrence. Spectrometric results were not useful in the prediction.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

BLANK PAGE

S/N 0102- LF- 014- 6601

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

Section	Subject	Page
	LIST OF ILLUSTRATIONS	2
	LIST OF TABLES	2
I	INTRODUCTION	
	A. Background	3
	B. Objective	3
II	AIRCRAFT PUMP CONSIDERATIONS	
	A. Introduction	4
	B. Operational Relevance	4
	C. Pump Wear Mechanisms	4
III	EXPERIMENTAL PROCEDURES/RESULTS	
	A. Test Apparatus Description	5
	B. Test Operation	13
	C. Failures During Operation	13
	D. Wear Debris Analysis	15
IV	CONCLUSIONS	22
V	RECOMMENDATIONS	22
	APPENDIX A - PHOTOGRAPHIC RECORD OF FERROGRAMS	23

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Simplified Schematic Diagram of Expanded Test System	6
2	Typical Aircraft Hydraulic Motor	7
3	Schematic Diagram of Expanded System	8
4	Front View of Expanded Test System	11
5	Rear View of Expanded Test System	12
6	Failed Motor Valve Plate and Cylinder Gap	14
7	Disassembled Valve Plate and Cylinder Assembly	16
8	Mating Faces of Valve Plate and Cylinder	17
9	Galled Surface of Bearing Inner Race	18
10	Close-up of Spalled Balls Removed from Bearing	19
11	Cylinder Valve Plate and Piston Assembly	20

LIST OF TABLES

Table	Title	Page
1	Laboratory Test Setup Components	10

I. INTRODUCTION

A. BACKGROUND

1. The ability to predict the failure of a mechanical device has long been the goal of maintenance engineers. Numerous techniques, such as vibration analysis, have been investigated in order to develop a technique with this predictive capability. Another technique, wear debris analysis, has been under investigation for application to fluid-lubricated systems. The basic premise underlying this technique is that a mechanical component will begin to generate wear particles long before any degradation of performance is noticed, and by observing various aspects of the debris, it is possible to predict when the system approaches and enters the wear-out portion of its life. By knowing this time, it is possible to take corrective action long before a system breakdown occurs.

2. The technique of wear debris analysis, also known as oil analysis, has been employed by the Navy for some time now to monitor the propulsion systems aboard its aircraft. This monitoring has taken the form of trending the quantities of certain metallic elements as obtained from a spectrometric analysis, and recently efforts are being made to introduce a system of optically characterizing the debris through a technique known as Ferrography.

3. In addition to the aircraft's engine, the hydraulic system is a prime candidate for monitoring for potential failures. In a previous effort (reference (a)), a study was undertaken to determine whether wear debris monitoring could be implemented for an aircraft hydraulic system. This study found that the majority of the system, actuator valves, etc., do not produce sufficient quantities of metallic wear debris to warrant monitoring. However, it was noticed during this investigation that a primary source of metallic debris was available at the pump case drain.

B. OBJECTIVE. The objective of this investigation was to study the feasibility of using wear debris analysis as a predictive maintenance tool for hydraulic pumps.

Ref: (a) NAVAIRENGCEN Report NAEC-92-158 of 10 May 1982: Application of Wear Debris Analysis to Aircraft Hydraulic Systems

II. AIRCRAFT PUMP CONSIDERATIONS

A. INTRODUCTION. High-performance Navy aircraft utilize hydraulic power for the operation of flight controls and various utility systems. A typical aircraft hydraulic system consists of two circuits, one supplying power to the flight controls and the other supplying power to both the flight control and the utility systems. The possibility exists that a failure of both hydraulic pumps could occur simultaneously and cause a complete loss of the flight controls and subsequent loss of the aircraft. A single pump failure would cause a mission abort and could jeopardize the aircraft's and crew's safety. Navy aircraft hydraulic pumps do not have a maintenance accessory record card, are not on a scheduled removal cycle, and remain on the aircraft until removed for unscheduled maintenance. In other words hydraulic pumps fly until failure.

B. OPERATIONAL RELEVANCE. In order to gain insights into the failure rates of pumps in the field, data from the Navy Maintenance and Material Management (3-M) System was analyzed. Data was reviewed for two typical aircraft types found in the inventory for a one-year operational period. During this time a total of 648 pump failures were reported, of which 175 resulted in mission aborts. The data indicates that approximately 85% of the 648 failures can in some way be related to wear. Had a predictive technique such as wear debris analysis been employed, this figure could have been reduced significantly.

C. PUMP WEAR MECHANISMS

1. Aircraft hydraulic systems are designed to produce and maintain fluid pressure and flow to satisfy flight control performance requirements. The pressure level utilized in most Navy aircraft systems is 3,000 psi. Variable displacement axial piston pumps are normally used as the prime hydraulic power source. Fixed displacement axial piston hydraulic motors, similar in design characteristics to the primary pumps, are normally used in the nonessential flight control, secondary systems or utility systems, where rotary actuation is required.

2. The hydraulic system pumps are normally aircraft-engine driven and operate continuously from engine startup through shutdown, exposing their internal components to continuous wear. The pump's critical parts experience rotating and sliding motion. The mechanisms of wear (abrasion, adhesion, and fatigue) may occur separately or in combination at the bearings, shafts, pistons, and cylinder blocks of the pump. The criticality of the main system hydraulic pumps makes them logical candidates for a more concentrated investigation of the early detection of abnormal pump wear and/or incipient failures through wear particle and debris analysis.

III. EXPERIMENTAL PROCEDURES/RESULTS

A. TEST APPARATUS DESCRIPTION

1. The test system developed under the initial phase of the project (reference (a)) had accumulated a total of 681.5 hours of operation. It was therefore decided to maintain the initial test system in the current phase of the project, so that additional wear time could be accumulated on the original components. It was also decided to maintain all existing power, control, and monitoring units for cost effectiveness. The test system was expanded to emphasize pump wear. This was accomplished by mechanically coupling two motors in a way that one motor drives the other motor, causing the latter to operate as a pump, thus enabling the formation of two independent fluid systems identified as systems A and B in Figure 1. The fluid motor portions of the motor/pump sets were hydraulically connected to the main pump output in system A. The pump portions of the motor/pump sets were hydraulically connected in fluid system B. The motors/pumps utilized in the project were actual aircraft quality components salvaged from the RA-5C aircraft. Figure 2 is a typical hydraulic motor used.

2. Five sets of fixed displacement motors/pumps were added to the initial test components. The expanded system forms two fluid circuits, one of which is a filtered actuator motor system and the other an unfiltered pump system. Figure 3 is the schematic diagram of the test system; the figure also identifies the locations of the sampling points and the temperature and pressure monitors. Table 1 is an itemized listing of the components identified in Figures 3, 4, and 5. Component locations are shown pictorially in Figures 4 and 5. The hydraulic test fluid used was a fire-resistant, synthetic hydrocarbon conforming to MIL-H-83282.

3. In the actuator-motor filtered fluid system, the same hydraulic power system that was used in the initial test phase is used to power the same actuator test arrangement. The five motors, item 27 in Figure 5, were added to this system. The main pump, item 17, is a pressure compensated, variable volume, piston type with a maximum displacement of 0.92 cubic inch per revolution. This pump is driven by a variable speed electric motor.

4. The fluid motor portions of the motor/pump sets were hydraulically connected to the main pump output. The displacement of this motor is 0.095 cubic inch per revolution. This permitted five motor/pump sets to be driven by the main pump. Filters were installed in the case drain lines of each fluid motor and in the system return line. Sampling points were added to these filters.

5. The motor portions of the motor/pump sets were mechanically coupled to the pumps, item 28 in Figure 3. This allowed the pump portion to have a completely independent fluid system. A single reservoir was used to supply hydraulic fluid to these pumps. Pressure relief valves, item 20, were installed in the pump pressure lines, providing back pressure to load

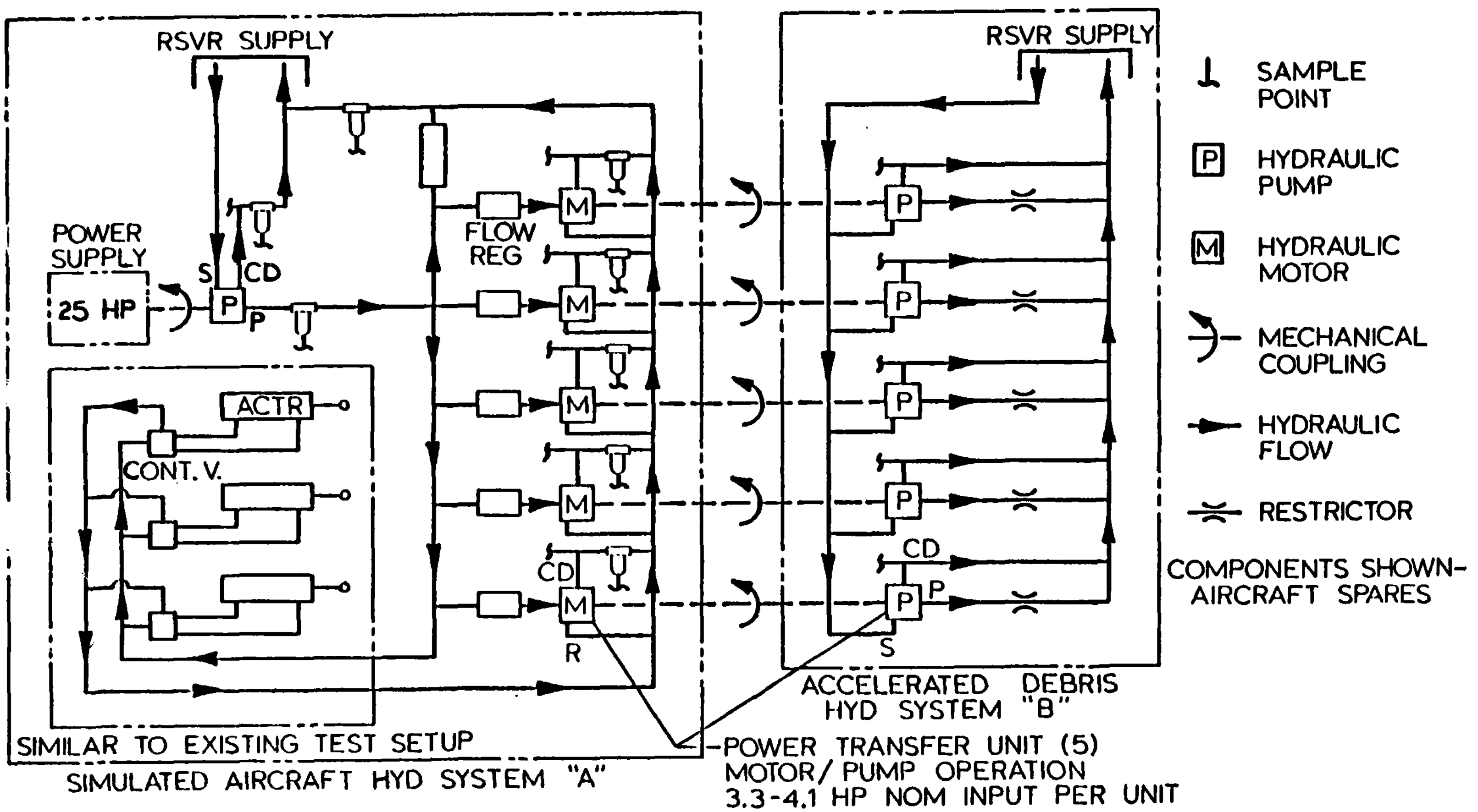


Figure 1 - Simplified Schematic Diagram of Expanded Test System

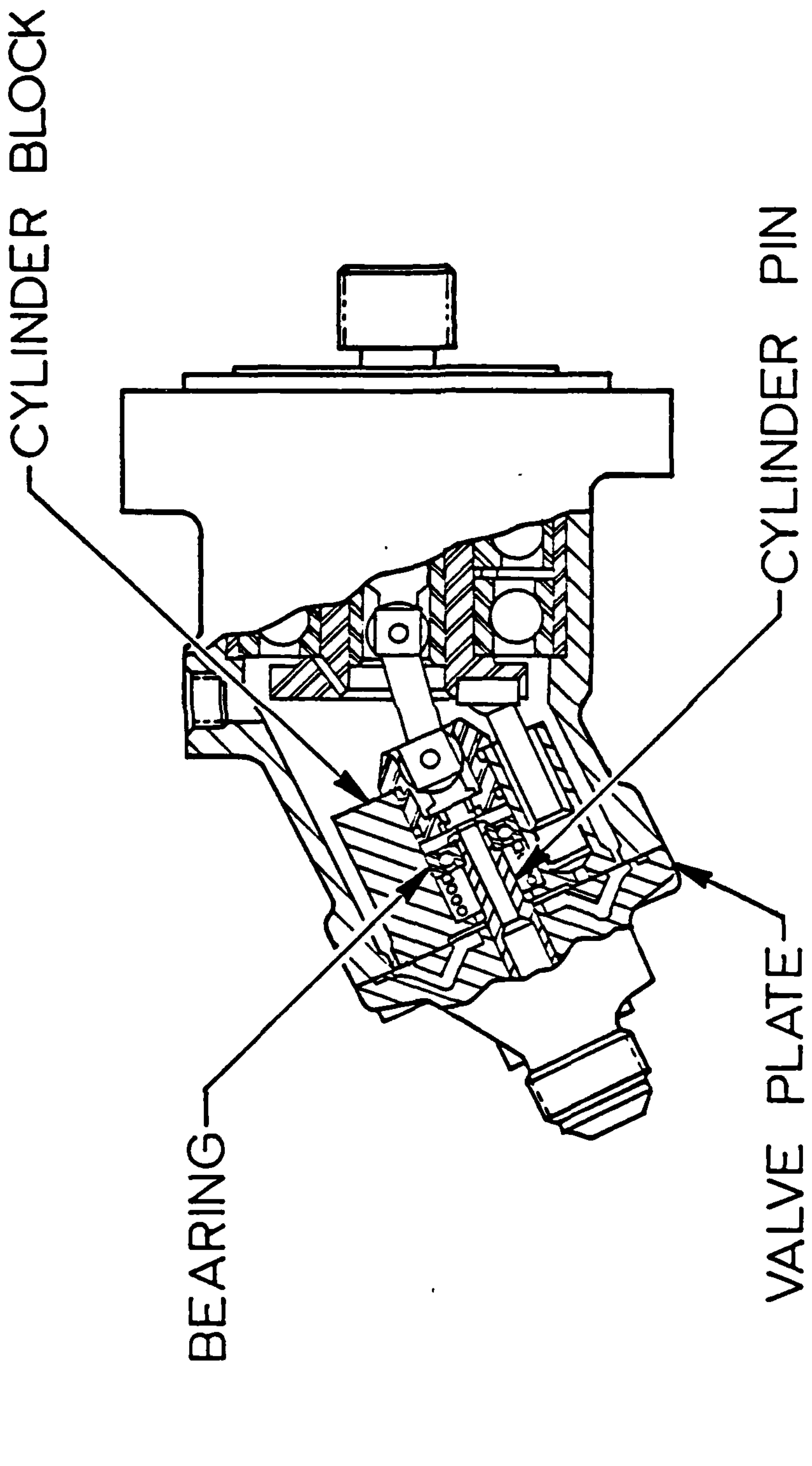


Figure 2 - Typical Aircraft Hydraulic Motor

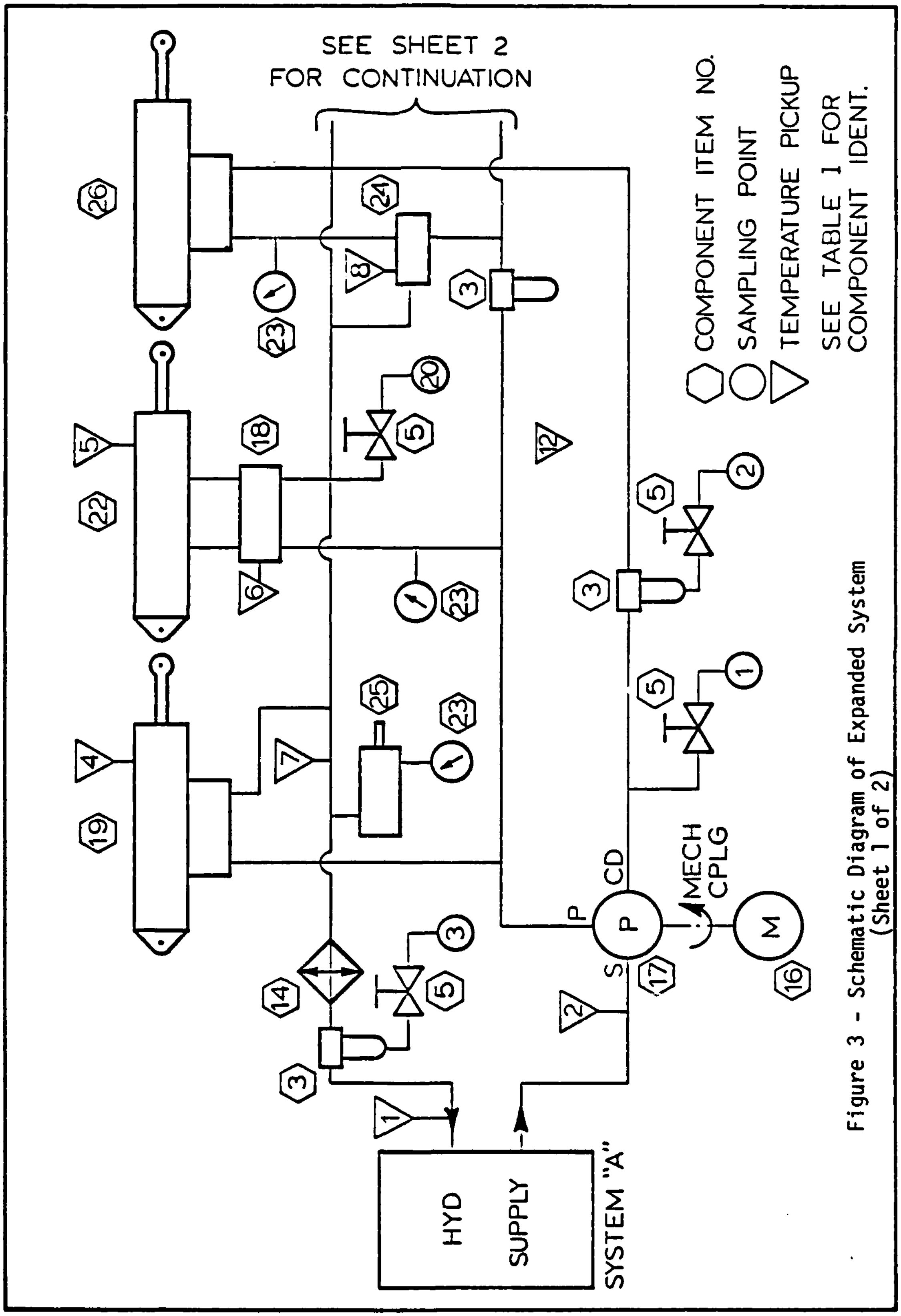


Figure 3 - Schematic Diagram of Expanded System
(Sheet 1 of 2)

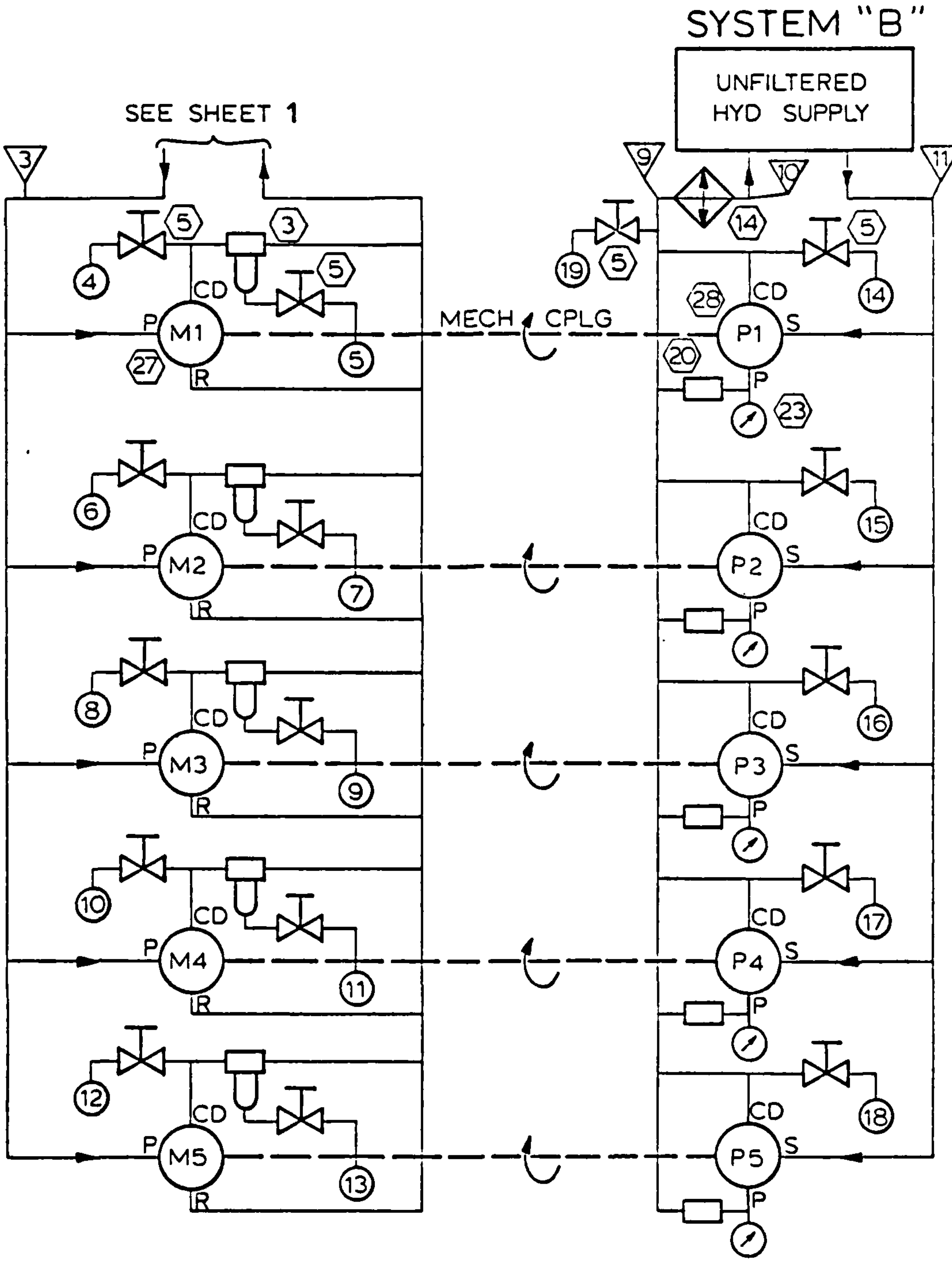


Figure 3 - Schematic Diagram of Expanded System
(Sheet 2)

TABLE 1. LABORATORY TEST SETUP COMPONENTS

Item	Component	Description
1	Lab Item	Valve, Air Shutoff
2	Lab Item	Regulator, Air Pressure
3	AC1183-16	Filter, Hydraulic
4	Lab Item	Gauge, Air Pressure
5	Lab Item	Valve, Hydraulic Sampling
6	Lab Item	Valve, Air Pressure Relief
7	Lab Item	Switch, Air Pressure Shutdown
8	F-72495	Switch, Hydraulic Float
9	263-586000-11	Reservoir, Hydraulic Fluid
10	Lab Item	Switch, Fluid Temperature Shutdown
11	Lab Item	Flowmeter
12	Lab Item	Temperature Sensor
13	Lab Item	Valve, Check
14	Lab Item	Heat Exchanger
15	Lab Item	Valve, Water Regulating
16	Lab Item	Motor, Electric, 25 hp Varidrive
17	51054	Pump, Hydraulic
18	1371-579327M1	Valve, Solenoid Operated Directional
19	275-587010-31	Actuator, Horizontal Surface Control
20	Lab Item	Valve, Hydraulic Pressure Relief
21	Lab Item	Regulator, Hydraulic Flow
22	298-581010-2	Actuator, Landing Gear
23	Lab Item	Gauge, Hydraulic Pressure
24	Lab Item	Valve, Hydraulic Pressure Reducing
25	Lab Item	Cylinder, Surge Damping
26	279-587015-11	Actuator, Dual Yaw Servo
27	MF24-3906-30BC	Motor, Hydraulic
28	MF24-3906-30BC	Pump, Hydraulic
29	Lab Item	Snubber, Pressure Gauge

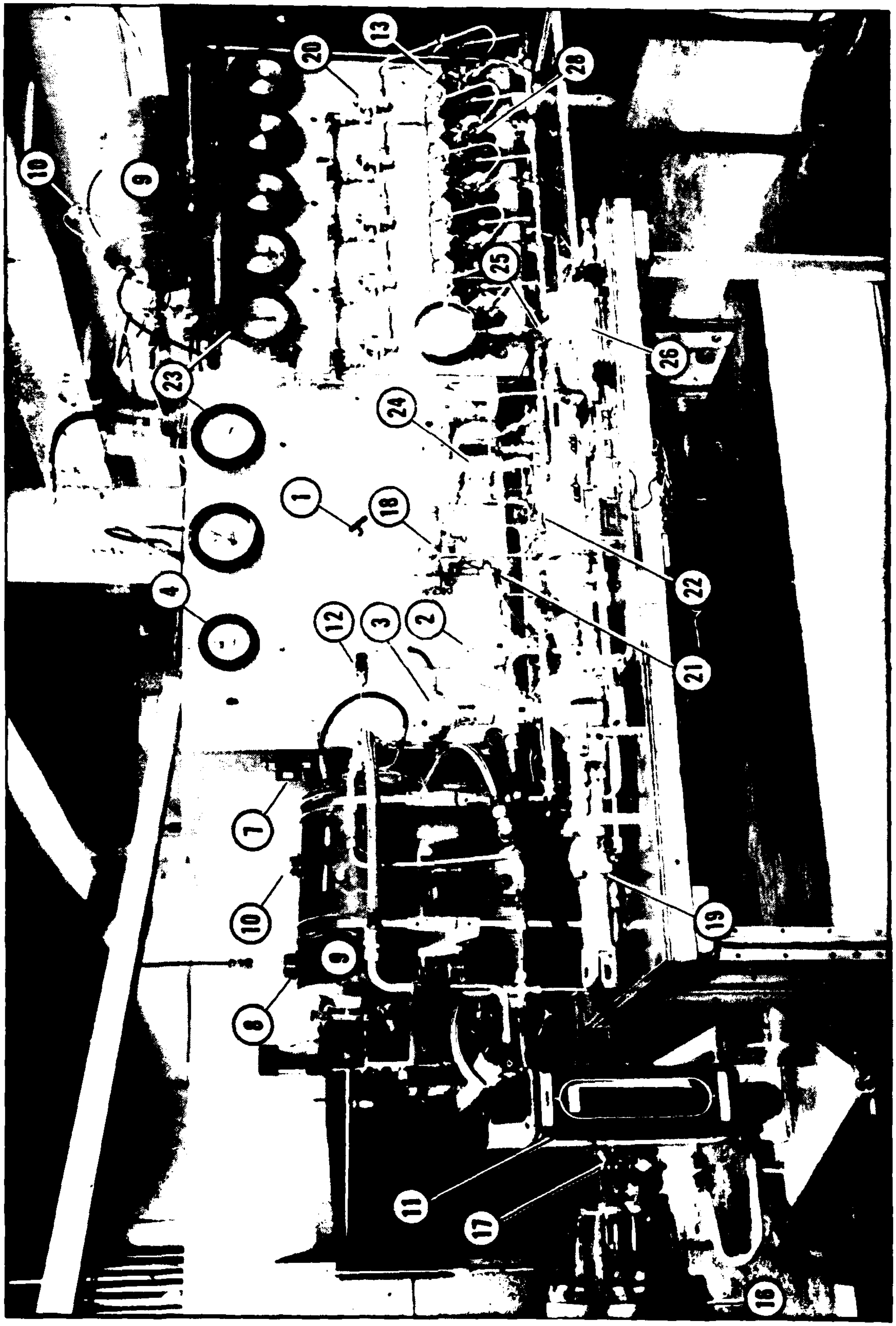


Figure 4 - Front View of Expanded Test Setup (see Table 1 for component ident)

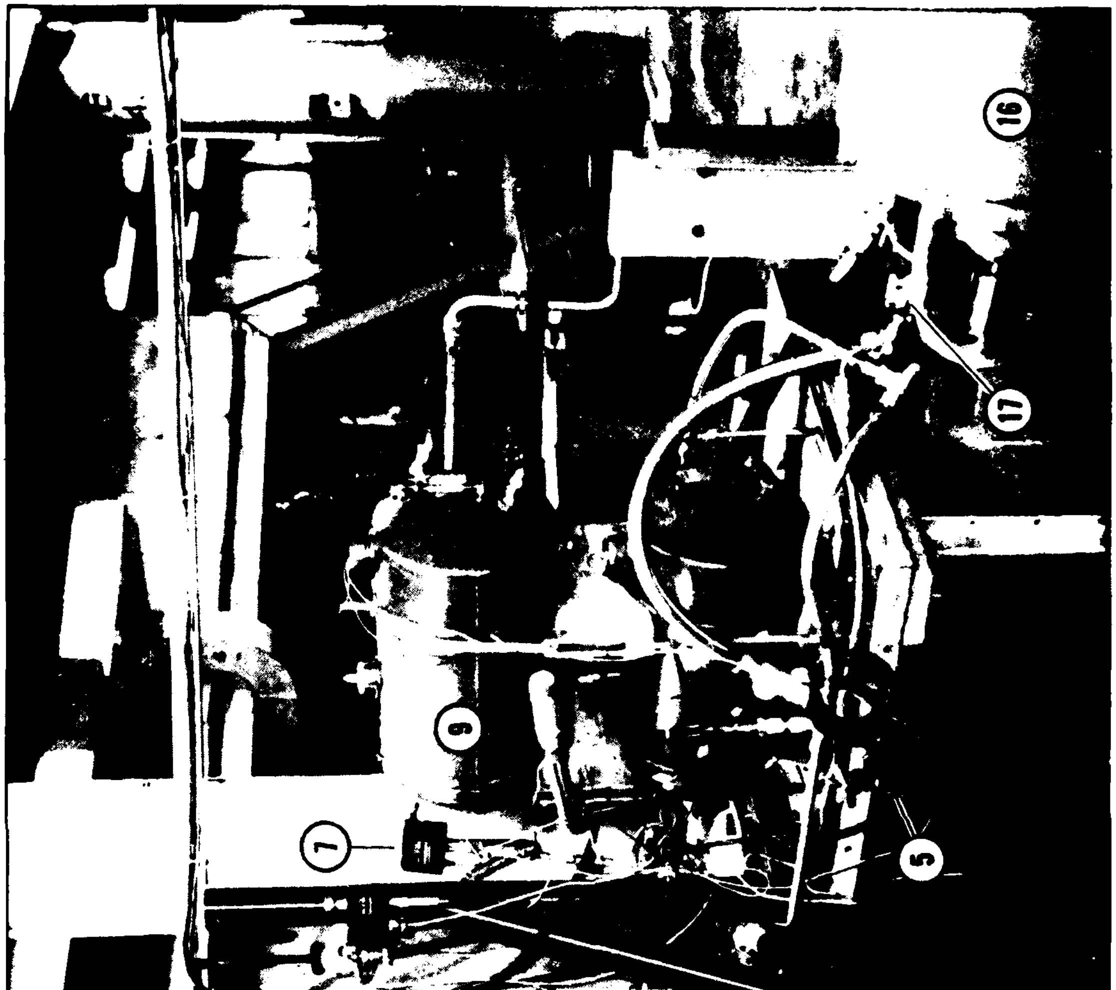


Figure 5 - Rear View of Expanded Test Setup (see Table 1 for component ident)

the pumps. While the fluid pressure available to the fluid motors was 3,000 psi, the torque efficiency loss of 17% through each fluid motor and hydraulic pump limited the pump back pressure load relief setting to 2,500 psi and caused the fluid motors to stall. Filters were not installed in the pump circuit in order to have a means of comparing the effects of a filtered hydraulic system with an unfiltered system.

6. Individual reservoirs were maintained for each of systems A and B. The reservoirs were of sufficient size to minimize the replenishment required during operation. Reservoirs were maintained at 50-psi pressure to prevent cavitation in the pumps.

7. System pressures and temperatures were monitored throughout the tests and maintained at normal operating levels.

B. TEST OPERATION

1. The test system was operated eight hours a day, five days a week, for eight weeks, with the exception of system shutdowns for maintenance or failure.

2. The types of samples obtained were circulating fluid samples and filter bowl accumulative debris samples from each of the filtered and unfiltered systems. Sampling points were located in the primary pump's case drain line and in the case drain lines of each of the motors/pumps; additional points were added to the case drain filters of the motors. Twenty sampling points were established; their locations are indicated in Figure 3.

3. During the operation, samples were extracted every 20 hours.

C. FAILURES DURING OPERATION

1. In a project of this type, failures must occur in order to have something to relate the wear-debris parameters to. To promote this, part of the system was run without filtration. It was felt that this condition would accelerate wear in a way that would tend to simulate the normal chain of events. In addition, induced wear through contaminants or implanted defects would not provide the desired types of results that could be provided by an unaltered system.

2. Unfortunately, hydraulic pumps are very reliable and only one failure occurred in the number 2 motor on system A at 191 hours of operation. The failure was revealed by a zero pressure gauge reading at the motor unit. The motor was removed from the system and disassembled.

3. Disassembly of the hydraulic motor portion of the unit revealed a gap between the valve plate and cylinder block, Figure 6, which allowed 3,000 psi fluid flow to bypass the motor pistons, resulting in an inoperative unit. Further disassembly of the cylinder block subassembly, Figures

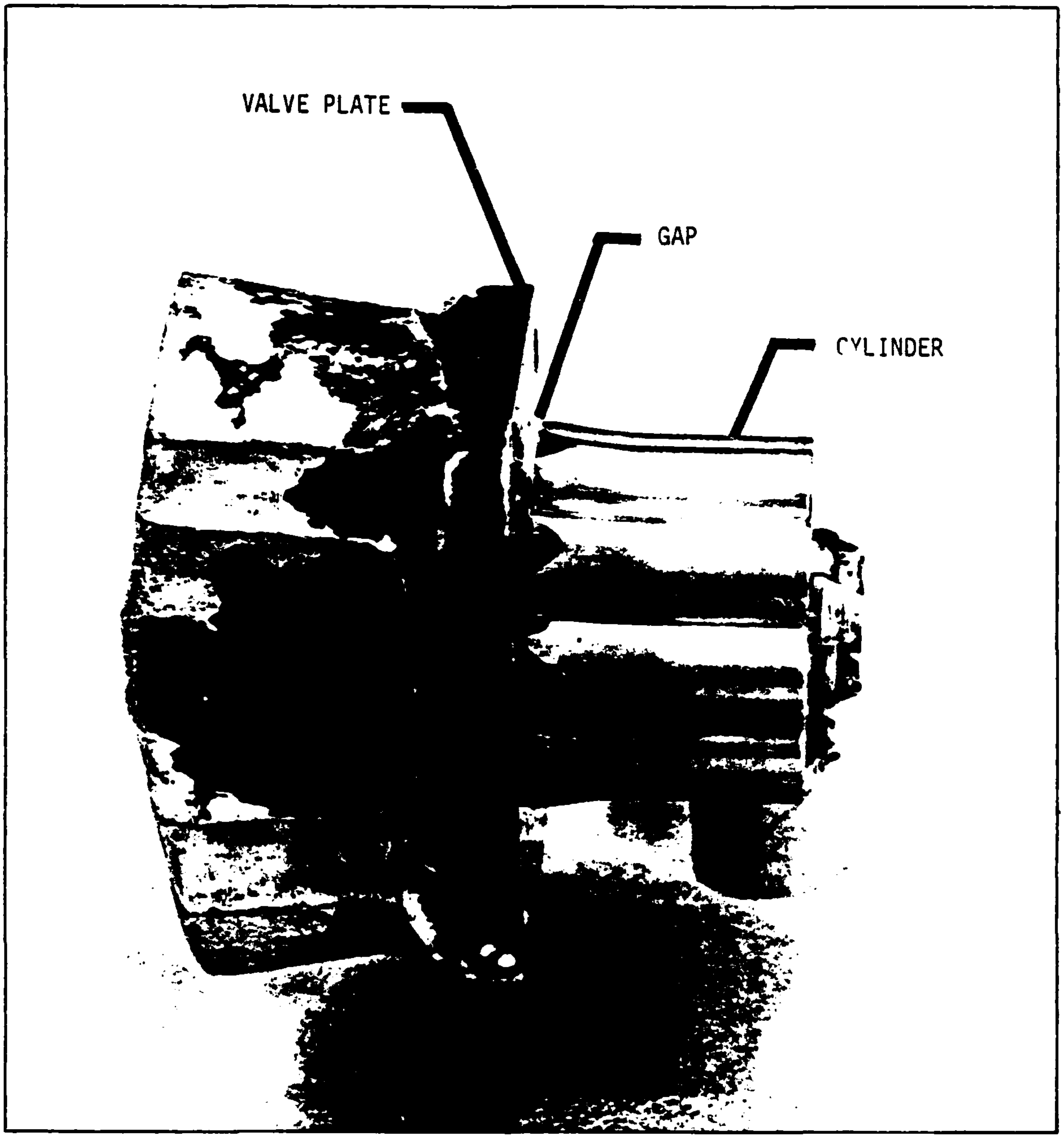


Figure 6 - Failed Motor Valve Plate
and Cylinder Gap

7 and 8, revealed that the valve plate and cylinder block gap resulted from a failed nonmetallic retainer for the balls in the cylinder block pin bearing. Failure of the retainer allowed the balls to escape from the bearing race, permitting free-play and gaps between the cylinder block and valve plate. Metallurgical analysis revealed galling of the bearing race, material fretting on the cylinder pin (Figure 9), and spalling of the bearing balls (Figure 10). The cylinder block, valve plate, and pistons from the failed unit are shown in Figure 11.

4. It was not apparent whether spalling of bearing balls or galling of the bearing race occurred prior to the ball retainer failure. The failed hydraulic motor is in the filtered system.

D. WEAR DEBRIS ANALYSIS. Two analysis methods were employed to collect wear debris information during the test period. One was an atomic emission spectrometer (identical to the type used in the Joint Oil Analysis Program) and analytical ferrography, a technique that allows the optical examination of entrained wear debris. As stated earlier the lone failure occurred at the number 2 motor/pump unit. Therefore the analysis for this particular location will be considered, that is, the samples extracted from point 6 (motor 2 case drain) and point 7 (motor 2 filter bowl). A total of 16 samples were taken from each of the locations at various times up until failure.

1. SPECTROMETRIC RESULTS, The results of the spectrometric analysis did not provide any information relative to a failure. In fact the readings, corrected for the base fluid, showed no variation other than $\pm$ 1 ppm throughout the test duration. The other sampling points denoted similar trends.

2. FERROGRAPHIC RESULTS.

a. Sample Location Number 6. The ferrographic analysis of the samples taken from sample location 6 revealed cutting and fatigue to be the dominant wear types. Samples analyzed during the early part of the test indicated a normal wear-in mode. At 114.5 hours of operation, a drastic increase in quantity and size of all particle types was observed, in particular cutting and fatigue particles. Succeeding samples were closely monitored, and at 134.5 hours of operation a number of spheres in the size range of 1 to 8 μm were observed. The presence of the spheres along with fatigue wear particles is typical of spalling in a ball bearing. Samples taken after this point still showed the presence of spheres and fatigue particles in reduced quantities. (Disassembly and inspection of the failed motor did indicate that spalling had occurred.) Samples taken at 173.5 hours of operation showed small quantities of very large nonmetallic debris. In hydraulic systems, nonmetallic particles of this size typically indicate a possible seal failure. (Inspection of the unit had indicated a failure of a nonmetallic retainer for the balls in the cylinder block pin bearing.) The next sample to be taken was after the motor assembly had been replaced; this showed large quantities of both metallic and nonmetallic debris. Normally, this would be considered abnormal, but it is felt that this material was residue from the failed component.

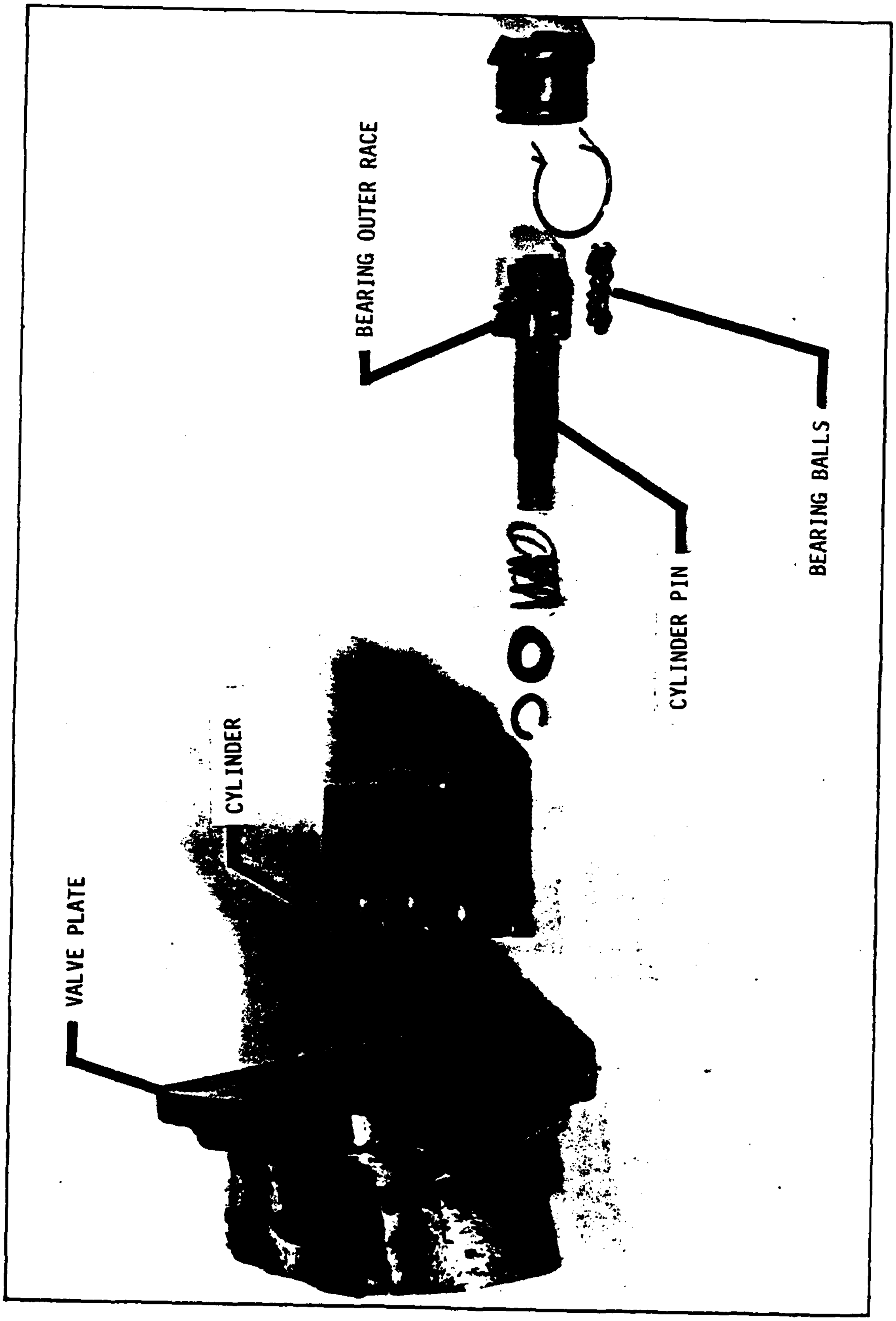


Figure 7 - Disassembled Valve Plate and Cylinder Assembly

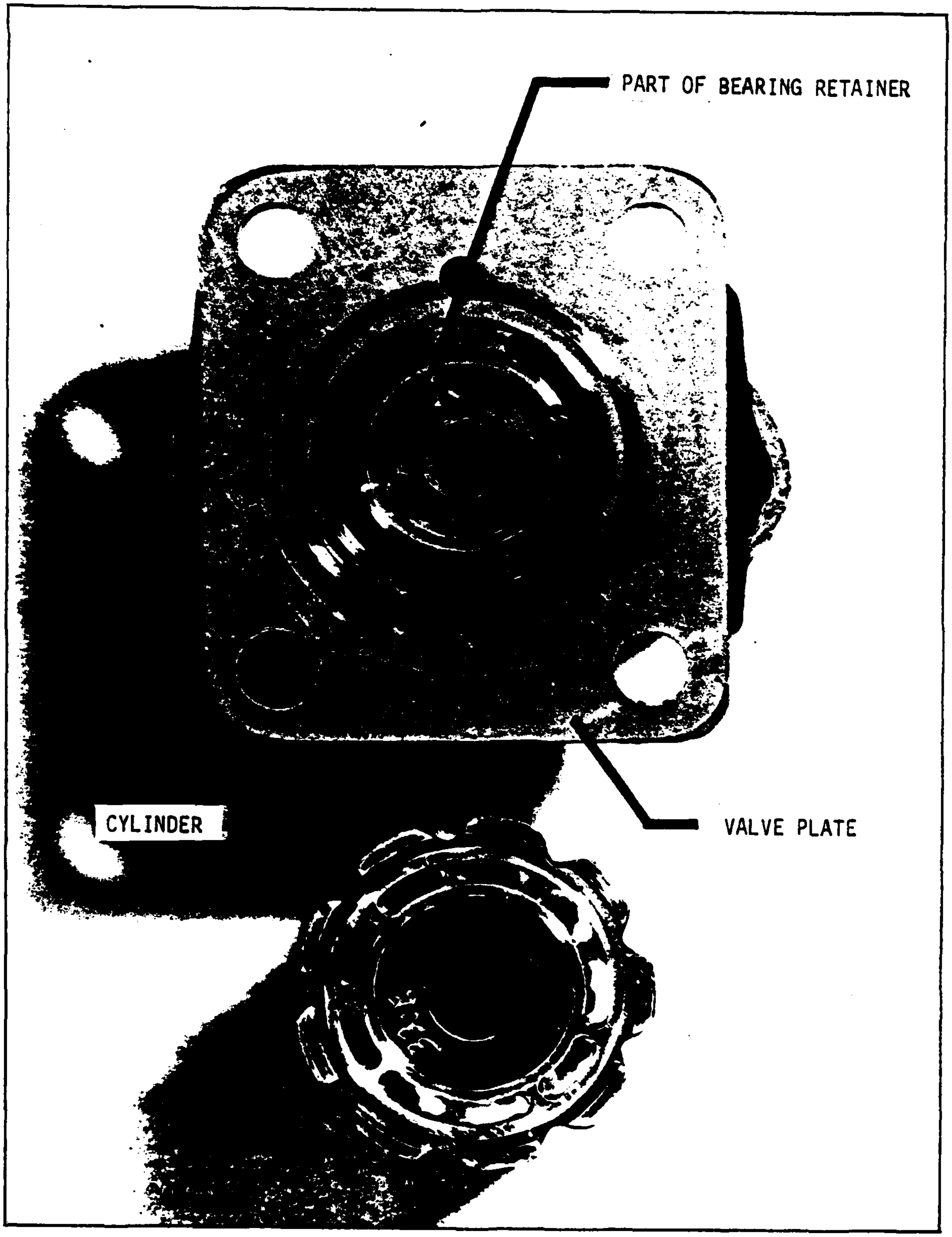


Figure 8 - Mating Faces of Valve Plate and Cylinder

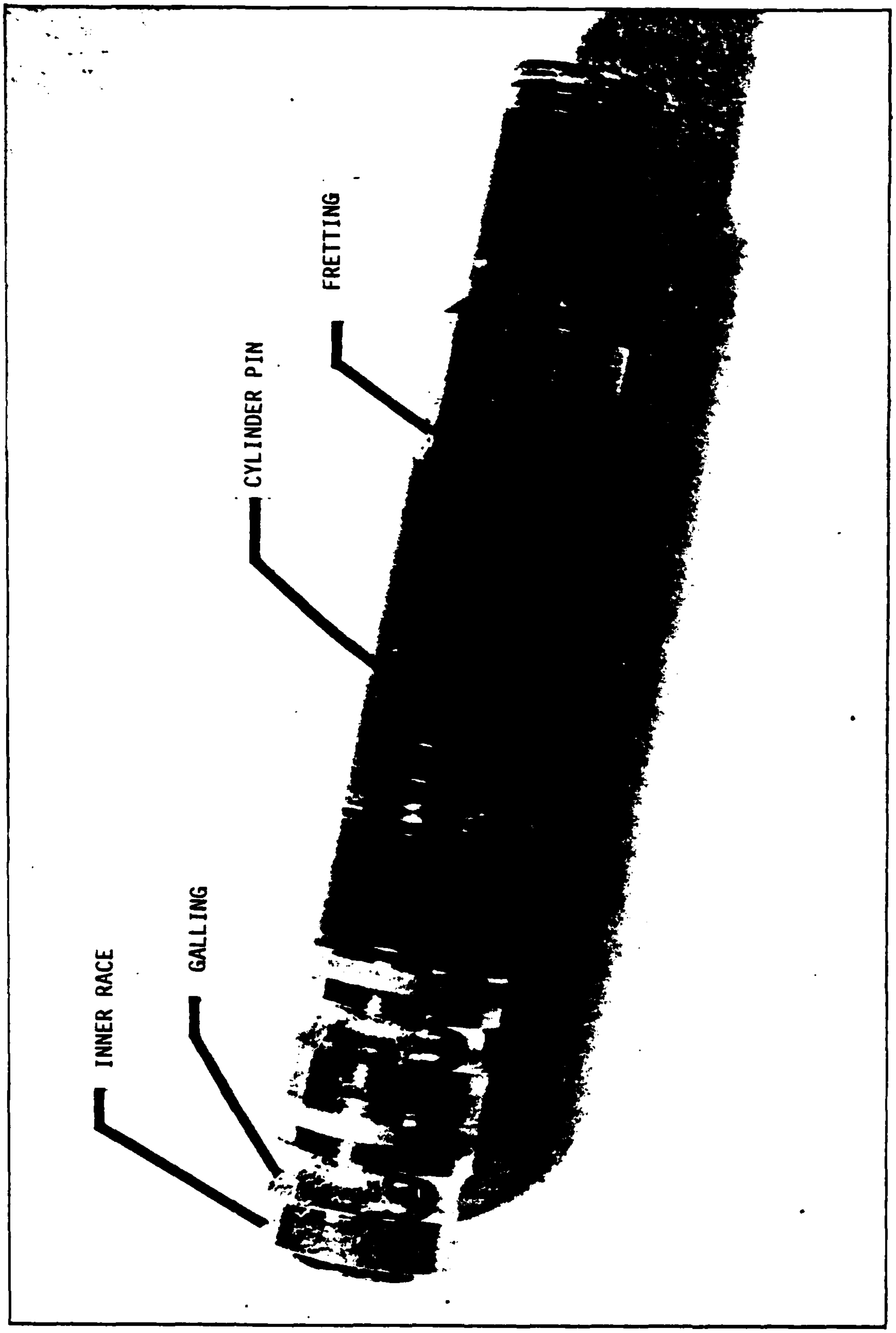


Figure 9 - Galled Surface of Bearing Inner Race

Figure 10 - Close-up of Spalled Balls, Removed From Bearing

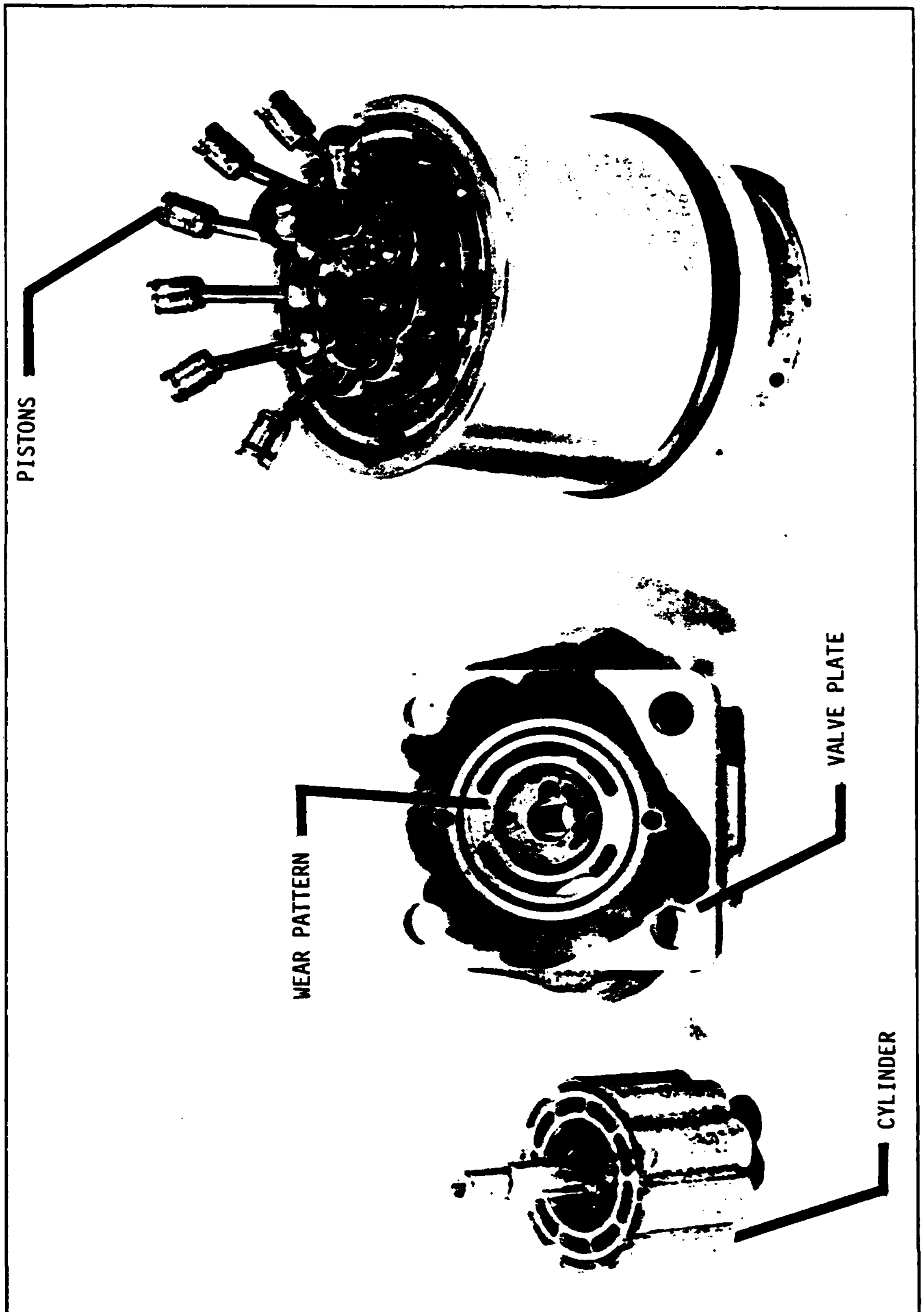


Figure 11 - Cylinder, Valve Plate, and Piston Assembly

Succeeding samples indicated particles of rubbing wear with small quantities of fatigue and cutting. Test operations were terminated soon after. Appendix A is a photographic record of the ferrograms from this sampling point.

b. Sample Location Number 7. The dominant particle types found at this location were sphere and fatigue. Spheres were present on almost every slide up to the failure point; sizes ranged from 2 to 15 μm. Fatigue particles increased in size after 57 hours of operation. Nonmetallic debris was more evident at this location as opposed to point 6, most notably after 173.5 hours of operation. Other than the previously mentioned results, the remaining sample analyses were almost identical to those of location 6.

IV. CONCLUSIONS

A. Although a limited amount of failure data was accumulated in this effort, we can still draw some useful conclusions from the results.

B. Ferrographic analysis is capable of predicting a potential failure in a hydraulic pump by monitoring the fluid which passes through the case drain. The use of this technique as a maintenance tool could prove to be a factor in enhanced reliability of hydraulic systems. By predicting failure in a pump, corrective action could be taken prior to the failure, resulting in reduced contamination of the remainder of the system. Another factor to consider is the prevention of catastrophic failures in systems, particularly aircraft, employing a single pump.

C. Spectrometric monitoring of a hydraulic system does not appear to be an effective method based on the capabilities of current generation equipment.

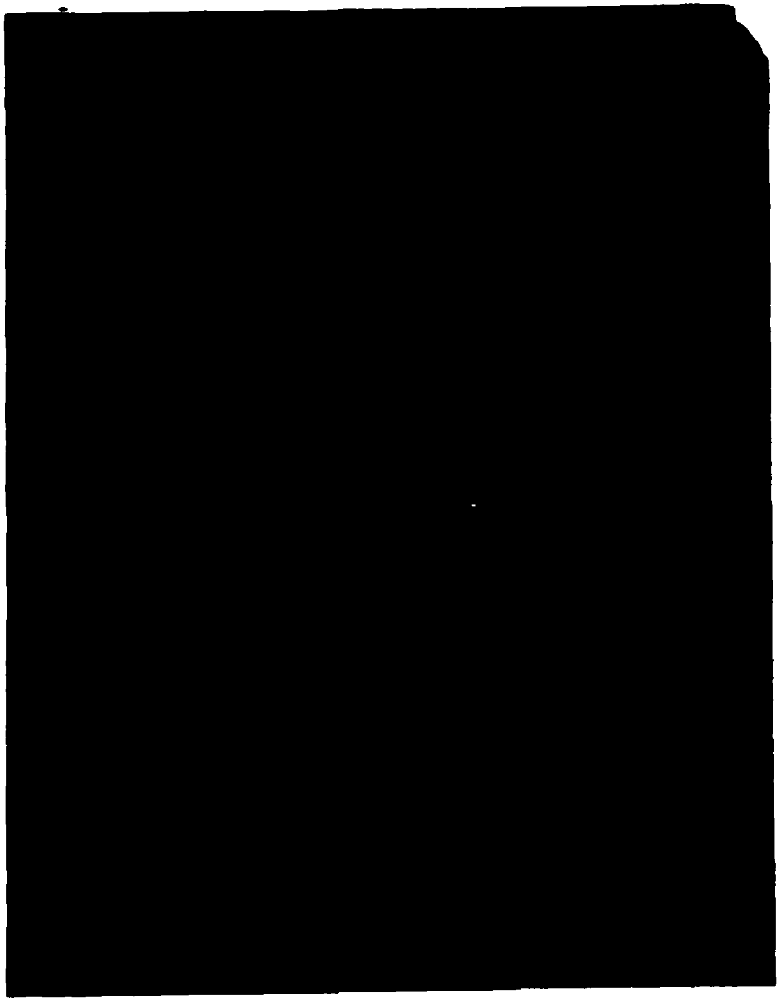
D. Finally, the results tend to indicate that a major source of hydraulic system contamination is external to the system and that this could be greatly reduced by exercising care when servicing the system.

V. RECOMMENDATION

A. Although the feasibility of utilizing wear debris analysis via Ferrography was demonstrated, it remains to be shown that it is economically viable to monitor the variety of hydraulic systems. Therefore, before any efforts are made to institute a program such as this, a detailed cost/benefit analysis is recommended.

APPENDIX A

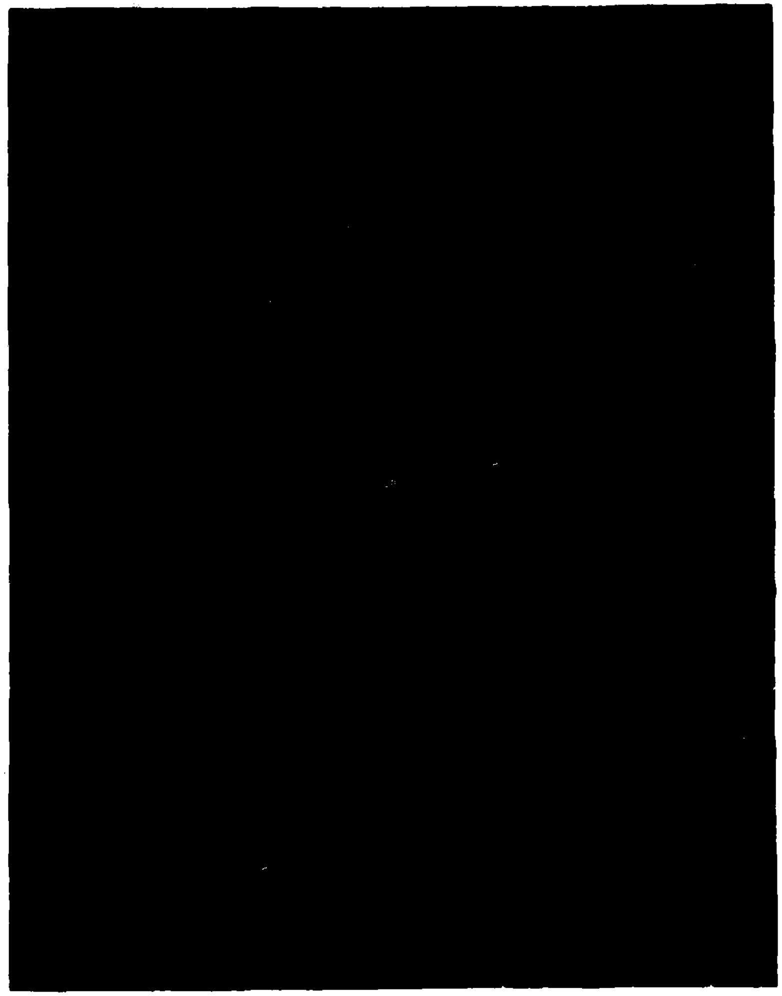
PHOTOGRAPHIC RECORD OF FERROGRAMS FOR SAMPLING POINT 6 BEGINNING AT 97 HOURS OF OPERATION



97.0 HRS 200X

ENTRY DEPOSIT

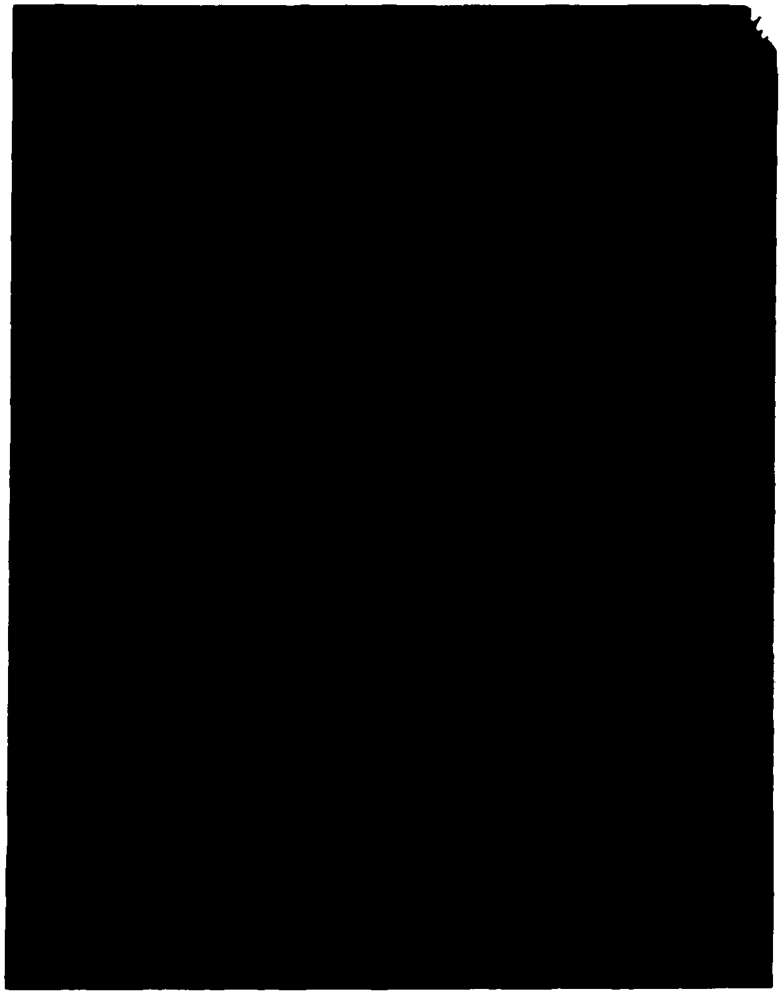
Mostly all rubbing wear particles. A few fatigue chunks can be seen.



114.5 HRS 200X

ENTRY DEPOSIT

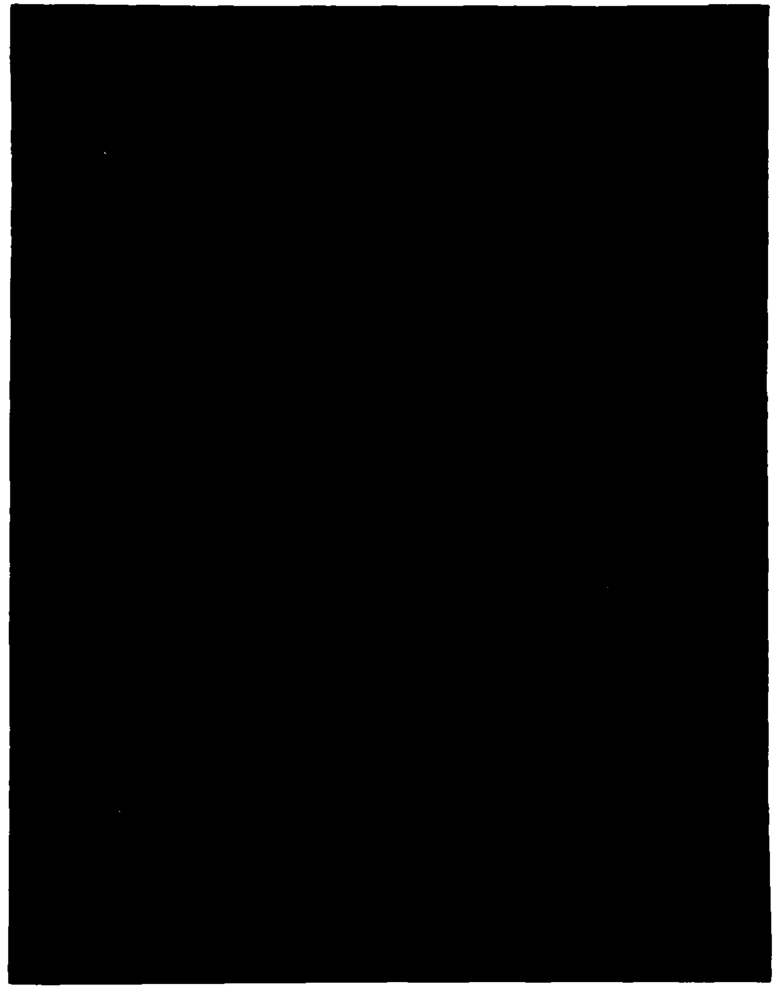
Note increase in number and size of particles from 97.0 hrs. Darker particles are typical hard steels. Yellow fatigue particles are pitted, slightly oxidized.



134.5 HRS 200X

ENTRY DEPOSIT

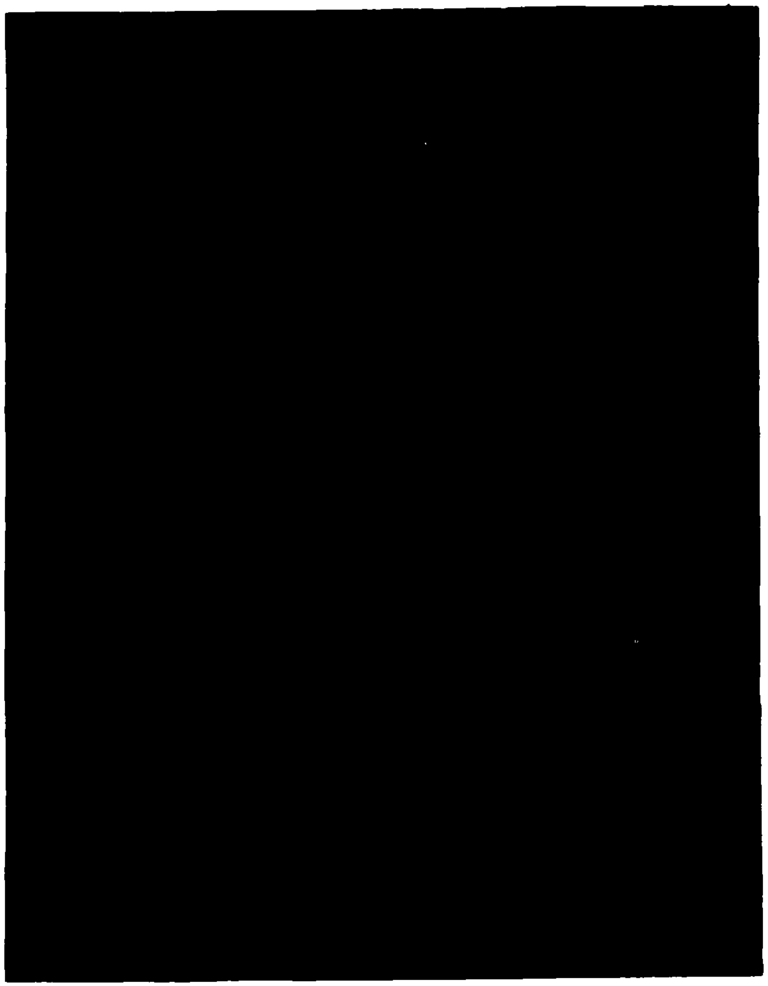
Under higher magnification many spheres were noticed along the entry string. Note two large yellow rubbing wear particles to upper left of particle string.



154.5 HRS 200X

ENTRY DEPOSIT

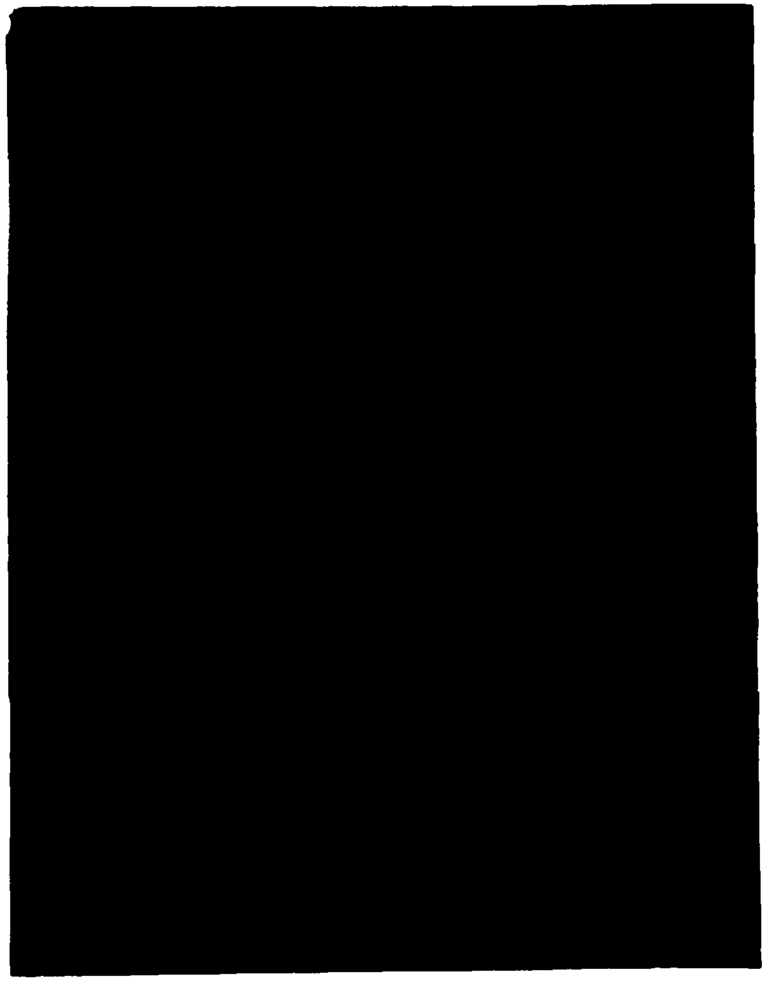
Entry deposit is composed mostly of dark metallo-oxide particles. Some cutting wear can be seen in upper portion of entry deposit.



173.5 HRS 200X

ENTRY DEPOSIT

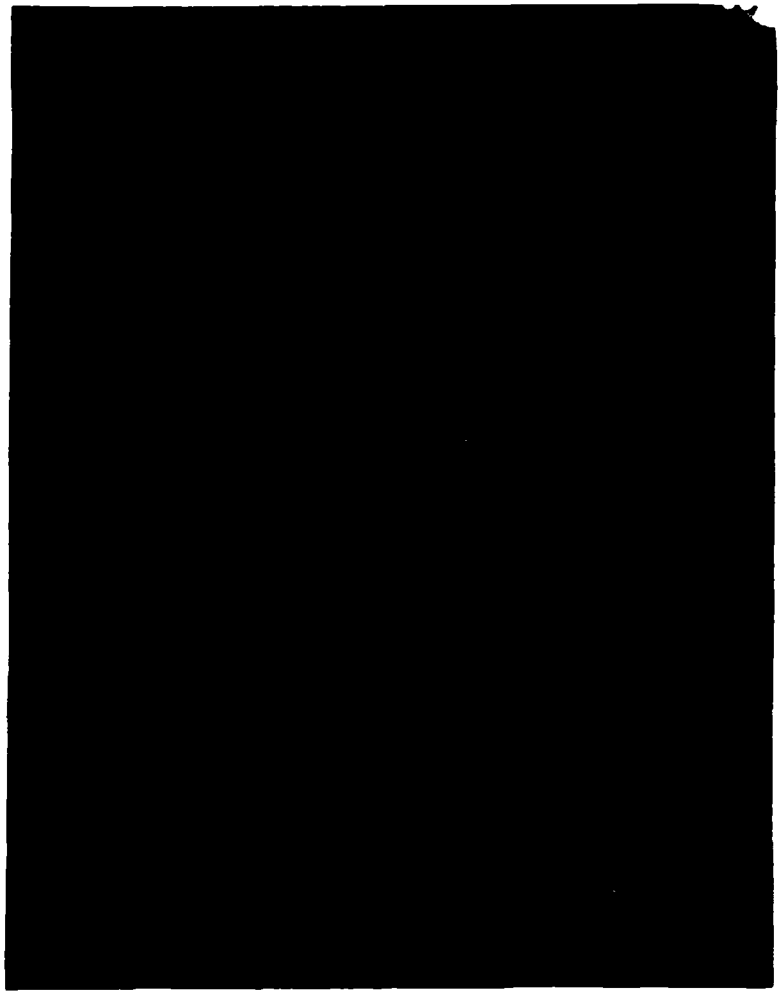
Yellow particles appear to be normal rubbing wear. Large amorphous particles appear to be wear debris from a nonmetallic seal.



194.5 HRS 200X

ENTRY DEPOSIT

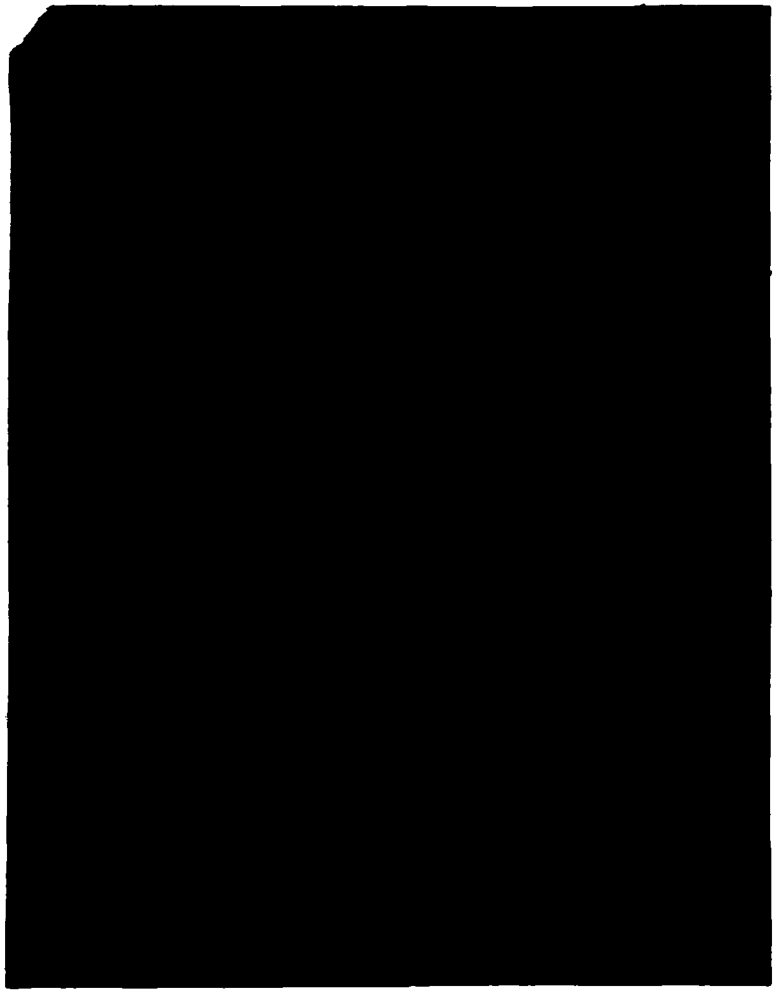
Particle string composed mostly of rubbing wear and a few fatigue chunks. An increase in the number of particles from 173.5 hrs can be seen. Note presence of large amorphous particle below entry string.



218.5 HRS 200X

ENTRY DEPOSIT

Slight decrease in number of particles from 194.5 hrs. Most rubbing wear particles are slightly oxidized. Some fatigue chunks can be seen to upper left of particle string. Large amorphous particle below the deposit appears to be more nonmetallic seal wear debris.



236.5 HRS 200X

ENTRY DEPOSIT

Drastic decrease in number of particles from 218.5 hrs. Mostly rubbing wear is evident. Note presence of large amorphous wear particle.

DISTRIBUTION LIST

NAVAIRENGCEN
- 1114 (2)
- 1115
- 902
- 92A1C
- 92A3 (30)
- 92A4
- 9271
- 92711

JOAP/TSC
ONR 430

NAVAIRSYSCOM
- AIR-00D4 (2)
- AIR-310G (3)
- AIR-411
- AIR-417
- AIR-552B
- AIR-5523 (3)

DTIC (12)

NAVAIREWORKFAC
- Alameda, CA
- Cherry Point, NC
- Norfolk, VA
- North Island, CA
- Jacksonville, FL
- Pensacola, FL

REVISION LIST

REVISION	PAGES AFFECTED	DATE OF REVISION

END

FILMED

9-83

DTIC